ZW), eurasisches Patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), europäisches Patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI-Patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Veröffentlicht:

— *mit internationalem Recherchenbericht*

— *vor Ablauf der für Änderungen der Ansprüche geltenden Frist; Veröffentlichung wird wiederholt, falls Änderungen eintreffen*

Zur Erklärung der Zweibuchstaben-Codes und der anderen Abkürzungen wird auf die Erklärungen ("Guidance Notes on Codes and Abbreviations") am Anfang jeder regulären Ausgabe der PCT-Gazette verwiesen.

(57) Zusammenfassung: Verfahren zur Bildregistrierung durch iterative Bestimmung einer hinsichtlich eines vorgegebenen Distanz- und Glattheitskriteriums optimalen Transformation, bei dem in den Bildern korrespondierende Kontrollpunkte garantierbar aufeinander abgebildet werden, durch (1) Initialisieren eines Iterationszählers und des initialen Verrückungsfeldes, (2) Bestimmen der numerischen Lösungen der nicht-linearen partiellen Differentialgleichung (PDE) mit dem aus einem vorgegebenen Glattheitskriterium ableitbarem Differentialope rator und den an vorgegebenen Kontrollpunkten lokalisierten Punktauswertefunktionalen, (3) Zusammenfassen der Interpolationsbedingungen, (4) Berechnen einer speziellen numerischen Lösung der PDE mit der auf der Basis des Distanzkriteriums und des aktuellen Verrückungsfeldes bestimmten Kraft und dem aus dem Glattheitskriterium abgeleiteten Differentialoperator, (5) Auswerten der speziellen Lösung an den Kontrollpunkten, (6) Bestimmen der Koeffizienten zur Berechnung einer aktualisierten Verrückung, (7) Aufdatieren des Verrückungsfelds und Erhöhen des Iterationszählers, (8) Überprüfen der Verrückung auf Konvergenz und (9) bei Nichterfüllen des Konvergenzkriteriums erneutes Durchlauf der Schritte (4) bis (8).

IMAGE REGISTRATION METHOD

PRIOR APPLICATIONS

This §371 National Phase patent application bases priority on International Application No. PCT/DE2003/003805, filed on November 18, 2003, which in turn bases priority on German Application No. DE 102 53 784.4, filed on November 19, 2002.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to an image registration or recording method, i.e. for the correction of geometrical differences in different representations of an object. These methods play an important part, e.g. in medical technology and, particularly, when analyzing tissue changes in conjunction with early cancer diagnosis.

2. Description of the Prior Art

Methods are already known which carry out an image registration on the basis of a distance criterion (Lisa Gottesfeld Brown, *A Survey of Image Registration Techniques,* ACM Computing Surveys, 24(4), 325-376, 1992; Jan Modersitzki, *Numerical Methods for Image Registration, Habilitation,* Institute of Mathematics, University of Luebeck, Germany, 2002). The general methodology is based on the optimization of a target function to be chosen in use-conforming manner and which is typically based on image intensities. In such

methods, apart from the image information, no further information is used for registration purposes. The registration result is only of an optimum nature in the sense of a global averaging. If particular significance is attached to specific, characteristic points in an application (such as e.g. the so-called anatomical landmarks in medical applications), such methods cannot be recommended.

Apart from image registration on the basis of a distance criterion, methods are also known which perform image registration exclusively on the basis of control points (Karl Rohr, *Landmark-Based Image Analysis,* Computational Imaging and Vision, Kluwer Academic Publishers, Dordrecht, 2001). In such methods, prospectively or retrospectively, corresponding control points are associated with the views to be registered, and are then matched by means of registration. The disadvantage of such methods is that the registration exclusively takes account of control points. Such methods cannot take account of further image information, such as e.g. image intensities. In the case of unsatisfactory registration results, a user can only attempt to improve them by skilled introduction of further control points. The insertion of further control points is based on subjective trial and error for which no guidelines exist, and in particular, there is no automated procedure.

The problem of the invention is to develop an image registration method which leads both to a perfect, guaranteed correspondence between a number of predetermined control points, and also an optimum result in the sense of the distance criterion.

SUMMARY OF THE INVENTION

According to the invention, the problem is solved by the iterative determination of a transformation optimum with respect to a predetermined distance and smoothness criterion, in which control points corresponding in the images are imaged on one another in guaranteed manner by initializing an iteration counter and the initial displacement, determining the numerical solutions of the nonlinear partial differential equation (PDE) with the differential operator derivable from a predetermined smoothness criterion and the point evaluation functions located at the predetermined control points, combining the interpolation conditions, calculating a specific numeral solution of the PDE with the force determined on the basis of the distance criterion and the actual displacement field and the differential operator derived from the smoothness criterion, evaluating the specific solution at the control points, determining the coefficient for calculating an updated displacement, updating the displacement field and raising the iteration counter, checking the displacement for convergence,

and in the case of non-fulfillment of the convergence criterion, repetition of the previous steps.

BRIEF DESCRIPTION OF THE DRAWINGS

Further advantages and features of the present invention can be gathered from the following description of the preferred embodiment relative to the attached drawing, wherein:

FIG. 1 illustrates a schematic block diagram of the image registration method of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The image registration method of the subject invention utilizes iterative determination of an optimum transformation with respect to a predetermined distance and smoothness criterion, wherein control points corresponding in the images can be imaged on one another in guaranteed manner, as shown in FIG. 1, by initializing the iteration counter and the initial displacement field **10**, determining the numerical solutions of the nonlinear partial differential equation (PDE) for the differential operator and the point evaluation functions located at the control points **20**, combining the interpolation conditions **30**, calculating a specific, numerical solution of the PDE for the differential operator and the force based on the actual displacement **40**, evaluating the specific solution at the control points **50**, determining the coefficients for calculating an updated displacement **60**, updating the

displacement field and raising the iteration counter **70**, and checking the displacement for convergence **80**. In the event of non-fulfillment of the convergence criterion, the sequence is repeated.

For simplification purposes, a view is referred to as a reference image (reference *R)*, and a further view, which is to be corrected, as a template (template *T*). From the formal standpoint, these are functions of a *d*-dimensional, real space or a subset $\Omega c R^d$ in the set of real numbers. Thus, to each *d*-dimensional point, $x \epsilon \Omega$ is associated through *R(x)* and *T(x)*, a value which can be interpreted, e.g. as a color or grey value.

In practical applications, particularly during every programming of the present method, the reference and template can be in discreet form. The images are then functions on a lattice (e.g. $\Omega=\{1,\ldots,n_1\}x\{1,\ldots,n_2\}$ for the dimension $d=2$) in a discreet set (e.g. in the set {0,...,255}) and can be interpreted as being formed from pixels. For the registration method, these restrictions and, in particular, the specific nature of the discreetization are unimportant. The restrictions are solely made for simplified description purposes. The method can be used in the same way on random *d*-dimensional data sets.

The function of image registration consists of the determination of a displacement function *u*, so that the

requirement $R(x)=T_u(x)$ is optimum well fulfilled with the short form $T_u(x):=T(x-u(x))$ for all $x\epsilon\Omega$. For calculating the template T_u deformed by u in the case of discreet, predetermined images, such as are of a conventional nature in image processing, an interpolation (e.g. d-linear) has to be performed because the displaced coordinates $x-u(x)$ are not necessarily located on the discreet lattice. The way in which such an interpolation takes place is unimportant for the registration method.

Over and beyond the aforementioned similarity, requirements must be made on the displacement smoothness and on the imaging characteristics with respect to a number of preselected control points. In the simplest case, the coordinates of each of the m control points $K^{T,j}$ of the template must be imaged on the, in each case, corresponding control point $K^{R,j}$ of the reference, $j=1,\ldots,m$. If the coordinates of the control points coincide, which may be ensurable by a preregistration, then $u=0$ applies at these points.

As is normally the case with optimization problems, the determination of a minimizer of the aforementioned distance criterion can take place iteratively by means of a gradient descent method. In principle, any random distance criterion can be selected. The forces associate with the standard distance criteria are given in the literature (Modersitzki

2002). The specific nature of the calculation of these forces is unimportant for the registration method.

In principle, any function known from the literature can be used as the smoothness criterion. From the smoothness criterion, it is possible to derive a partial differential operator *A*. These operators are known for the criteria used in the literature (Modersitzki 2002). The sought displacement *u* can then be characterized as a solution of a nonlinear, partial differential equation (PDE).

For determining a numerical solution of this PDE, use is made of a finite differential approximation of the differential operator, which then leads to an equation system for the lattice values of the displacement. However, the specific discreetization of the differential equation lacks significance for the registration method.

This procedure coincides with the method based solely on the distance criterion, and the smoothness criterion. The new aspect consists of a suitable binding in of the predetermined control points into the displacement calculation, in which a correspondence of the control points can be guaranteed. As methods are already known for the determination of the displacement based on the distance and smoothness criterion, a method is given here which combines partial solutions in an appropriate manner so as to give an overall solution, e.g. in

the form

$$u_e(x) = v^0_e(x) + \sum_{j=1}^{m} \lambda^e_j v^j_e(x), \qquad x \in \Omega, \qquad e=1,\ldots,d.$$

A is the differential operator associated with the smoothness term and f is the field of forces belonging to the distance criterion, so that v^0 is a numerical solution of $Av^0 = -f$, the functions v^j are numerical solutions of the distributional PDE $Av^j = \delta^j$, $j=1,\ldots,m$, in which δ^j locates the point selection function (Dirac impulse) at control point $K^{T,j}$. The specific, numerical method for the solution of the PDE is unimportant for the registration method.

From the mathematical standpoint, v^j, $j=1,\ldots,m$ are Green's functions of the differential operator A, representing a solution of the PDE at the predetermined single point displacement. A suitable linear combination of these Green's functions consequently ensures that in the overall method, in the required manner, all the control points are imaged on one another.

The function v^0 is so determined by means of an iterative method that the distance criterion is minimized, while maintaining the required smoothness. The weight functions λ^e_j are so adapted that the control points are imaged in the required way.

The initialization of the program requires the selection of a distance and a smoothness criterion, or the force derivable from said criteria and the differential operator. On the basis of the point evaluation functions located at the control points, it is then possible to determine the Green's functions v^j, $j=1,\ldots,m$ with a numerical method. They are not changed during the further course of the method.

The inventive initialization is followed by a standard iteration procedure, during which there is a gradient descent, while taking account of the control points. No human intervention is needed. Thus, the described method combines the advantages of methods based on distance criteria (particularly, automatability and on an average optimum registration) with those of the control point method (guaranteed registration of distinguished points), and on predetermining an initial set of control points, give reproducible, optimum results independent of the user or computer program. No important part is played by computer code details in the final result of the image registration, and they only influence the requisite computing time and memory requirements.

The images to be registered can be digital images, pixels, JPEG, wavelet-based objects or acoustic signals.

The linear equation systems occurring in the method can be

solved directly, indirectly, iteratively or by multigrid, and for the method use can be made of a reference coordinate system imaged by Euler or Lagrange coordinates.

The invention also proposes the registration of one, two or three-dimensional, and sequences of one, two or three-dimensional objects, as well as the use of control points in the form of anatomical landmarks, fiduciary markers or other characteristic quantities.

The distance criterion proposed is based on intensity, edge, corner, surface normal or level set or on the "sum of squared differences", L_2 distance, correlation, correlation variants, mutual information or mutual information variants.

The force terms associated with the distance quantity are to be calculated by finite difference methods or gradient formation, and the smoothness criterion used to be physically motivated by means of an elastic potential, or a fluid approach or diffusive or curvature approaches based on time or space derivatives of the displacement.

The boundary conditions of the differential operator are advantageously given by explicit or implicit, Neumann, Dirichlet, sliding, bending or periodic boundary conditions.

The nature of the discreetization of the differential operator should be based on finite differences, finite volume, finite elements, Fourier methods, series expansions, filter

techniques, collocations or multigrid, and interpolation is to be performed d-dimensionally by means of splines or wavelets.

Finally, displacement can be explicitly updated by means of the increment of the displacement or its time derivative.

AMENDED CLAIMS

Having thus described the invention, what is claimed and desired to be secured by Letters Patent is:

Claims 1-10 (canceled).

11. (new) A method for registration of images by iterative determination of an optimum transformation with respect to a predetermined distance and smoothness criterion, wherein control points corresponding in the images can be imaged on one another in guaranteed manner, the steps of the image registration method comprising:

(a) initializing an iteration counter and displacement field;

(b) determining the numeral solutions of the nonlinear partial differential equation (PDE) with the differential operator derivable from a predetermined smoothness criterion and the point evaluation functions located at the predetermined control points;

(c) combining the interpolation conditions;

(d) calculating a specific numerical solution of the partial differential equation (PDE) with the force determined on the basis of the distance criterion and the actual displacement field, the differential operator derived from the smoothness criterion;

(e) evaluating the specific solution at the control points;

(f) determining the coefficients for calculating an updated displacement;

(g) updating the displacement field and raising the iteration counter; and

(h) checking the displacement for convergence.

12. (new) The image registration method of Claim 11, wherein steps (d) through (h) are repeated for non-fulfillment of the convergence criterion.

13. (new) The image registration method of Claim 11, wherein the interpolation is performed *d*-dimensionally by means of splines or wavelets.

14. (new) The image registration method of Claim 11, wherein displacement is updated by means of the increment of the displacement or its time derivative.

15. (new) The image registration method of Claim 11, wherein one, two or three-dimensional objects are registered.

16. (new) The image registration method of Claim 15, wherein the sequences of one, two or three-dimensional objects are registered.

17. (new) The image registration method of Claim 11, wherein control points are characterized by anatomical landmarks, fiduciary markers or other quantities.

18. (new) The image registration method of Claim 11, wherein the distance criterion is based on intensity, edge, corner, surface normal or level set, sum of square differences, L_2 distance, correlation, mutual information or other variants.

19. (new) The image registration method of Claim 11, wherein force terms of distance quantity are calculated by means of finite difference methods or gradient formation.

20. (new) The image registration method of Claim 11, wherein smoothness criterion is enforced by means of elastic potential, fluid approach, or diffusive or curvature approaches based on time and space derivatives.

21. (new) The image registration method of Claim 11, wherein boundary conditions of the differential operator are specified as explicit or implicit, Neumann, Dirichlet, sliding, bending or periodic.

22. (new) The image registration method of Claim 19, wherein discreetization of the differential operator is based on finite differences, finite volume, finite elements, Fourier methods, series expansions, filter techniques, collocations or multigrid.

IMAGE REGISTRATION METHOD

ABSTRACT

An image registration method iteratively determining a transformation that is optimal regarding a given distance criterion and smoothness criterion. The method allowing corresponding landmarks in the images to be definitely represented on top of each other, the registered images being derivative of digital images, pixels, JPEG, wavelet-based or acoustic signals.

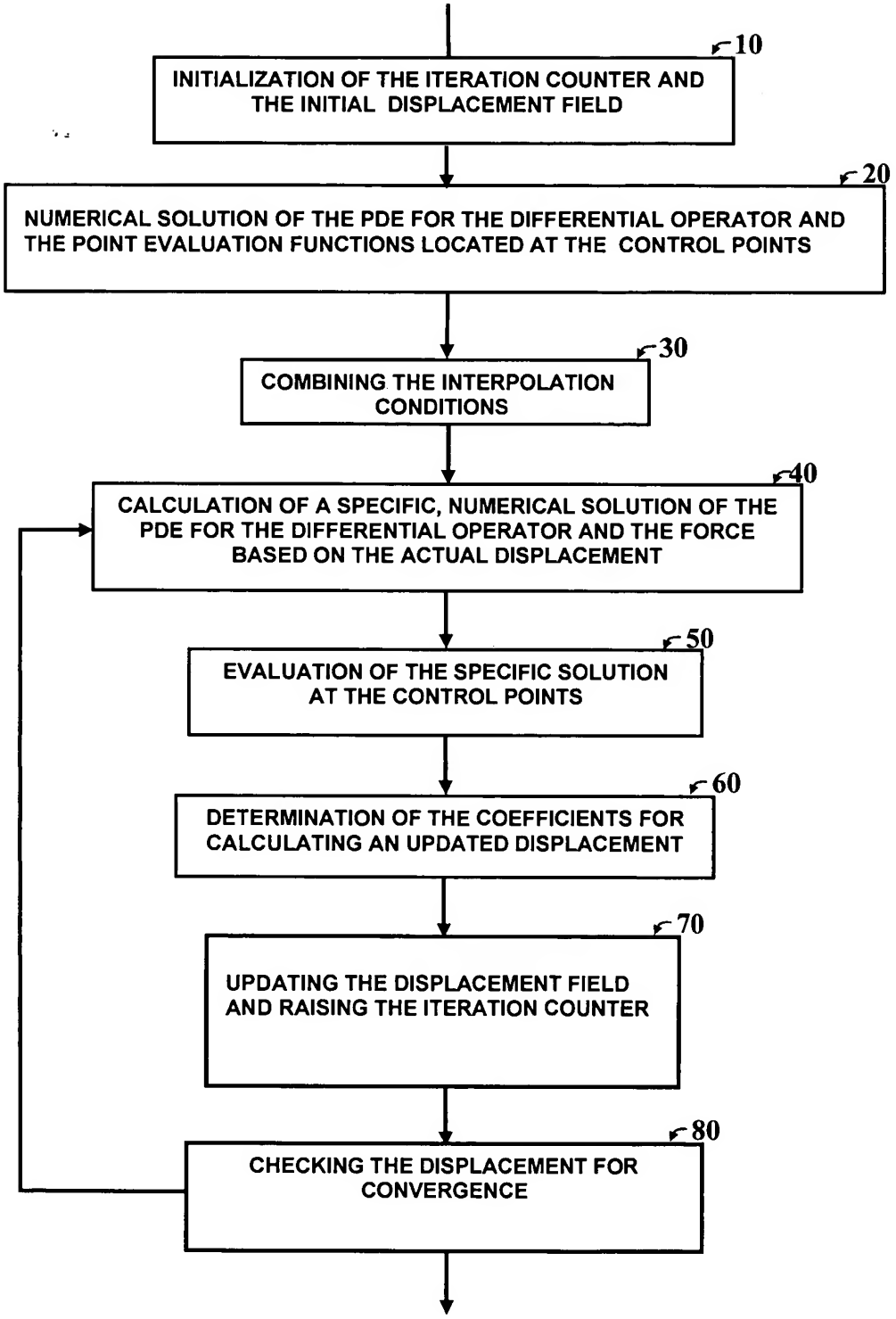
10
INITIALIZATION OF THE ITERATION COUNTER AND THE INITIAL DISPLACEMENT FIELD
20
NUMERICAL SOLUTION OF THE PDE FOR THE DIFFERENTIAL OPERATOR AND THE POINT EVALUATION FUNCTIONS LOCATED AT THE CONTROL POINTS
30
COMBINING THE INTERPOLATION CONDITIONS
40
CALCULATION OF A SPECIFIC, NUMERICAL SOLUTION OF THE PDE FOR THE DIFFERENTIAL OPERATOR AND THE FORCE BASED ON THE ACTUAL DISPLACEMENT
50
EVALUATION OF THE SPECIFIC SOLUTION AT THE CONTROL POINTS
60
DETERMINATION OF THE COEFFICIENTS FOR CALCULATING AN UPDATED DISPLACEMENT
70
UPDATING THE DISPLACEMENT FIELD AND RAISING THE ITERATION COUNTER
80
CHECKING THE DISPLACEMENT FOR CONVERGENCE

FIG. 1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/DE 03/03805

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G06T7/00 G06T3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MAINTZ J B A ET AL: "A SURVEY OF MEDICAL IMAGE REGISTRATION" MEDICAL IMAGE ANALYSIS, OXFORDUNIVERSITY PRESS, OXFORD, GB, vol. 2, no. 1, 1998, pages 1-37, XP001032679 ISSN: 1361-8423 sec. 4.2, "Intrinsic registration methods" page 4 -page 7 --- -/--	1-10

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 April 2004	26/04/2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Werling, A

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INTERNATIONAL SEARCH REPORT

I Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BROWN L G: "A SURVEY OF IMAGE REGISTRATION TECHNIQUES" ACM COMPUTING SURVEYS, NEW YORK, NY, US, vol. 24, no. 4, 1 December 1992 (1992-12-01), pages 325-376, XP000561460 ISSN: 0360-0300 cited in the application the whole document	1-10
A	WO 02/056241 A (VEMURI BABA C ;UNIV FLORIDA (US)) 18 July 2002 (2002-07-18) abstract	1-10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/DE 03/03805

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 02056241 A	18-07-2002	WO 02056241 A1	18-07-2002

INTERNATIONALER RECHERCHENBERICHT

Aktenzeichen
PCT/DE 03/03805

A. KLASSIFIZIERUNG DES ANMELDUNGSGEGENSTANDES
IPK 7 G06T7/00 G06T3/00

Nach der Internationalen Patentklassifikation (IPK) oder nach der nationalen Klassifikation und der IPK

B. RECHERCHIERTE GEBIETE

Recherchierter Mindestprüfstoff (Klassifikationssystem und Klassifikationssymbole)
IPK 7 G06T

Recherchierte aber nicht zum Mindestprüfstoff gehörende Veröffentlichungen, soweit diese unter die recherchierten Gebiete fallen

Während der internationalen Recherche konsultierte elektronische Datenbank (Name der Datenbank und evtl. verwendete Suchbegriffe)
EPO-Internal, WPI Data, INSPEC

C. ALS WESENTLICH ANGESEHENE UNTERLAGEN

Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
A	MAINTZ J B A ET AL: "A SURVEY OF MEDICAL IMAGE REGISTRATION" MEDICAL IMAGE ANALYSIS, OXFORDUNIVERSITY PRESS, OXFORD, GB, Bd. 2, Nr. 1, 1998, Seiten 1-37, XP001032679 ISSN: 1361-8423 sec. 4.2, "Intrinsic registration methods" Seite 4 -Seite 7 --- -/--	1-10

[X] Weitere Veröffentlichungen sind der Fortsetzung von Feld C zu entnehmen

[X] Siehe Anhang Patentfamilie

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Datum des Abschlusses der internationalen Recherche	Absendedatum des internationalen Recherchenberichts
15. April 2004	26/04/2004

Name und Postanschrift der Internationalen Recherchenbehörde	Bevollmächtigter Bediensteter
Europäisches Patentamt, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Werling, A

C.(Fortsetzung) ALS WESENTLICH ANGESEHENE UNTERLAGEN

Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
A	BROWN L G: "A SURVEY OF IMAGE REGISTRATION TECHNIQUES" ACM COMPUTING SURVEYS, NEW YORK, NY, US, Bd. 24, Nr. 4, 1. Dezember 1992 (1992-12-01), Seiten 325-376, XP000561460 ISSN: 0360-0300 in der Anmeldung erwähnt das ganze Dokument	1-10
A	WO 02/056241 A (VEMURI BABA C ;UNIV FLORIDA (US)) 18. Juli 2002 (2002-07-18) Zusammenfassung	1-10

INTERNATIONAL[redacted]RECHERCHENBERICHT

[redacted]s Aktenzeichen
PCT/DE 03/03805

Im Recherchenbericht angeführtes Patentdokument	Datum der Veröffentlichung	Mitglied(er) der Patentfamilie	Datum der Veröffentlichung
WO 02056241 A	18-07-2002	WO 02056241 A1	18-07-2002